THE EFFECTS OF CARBON, OXYGEN, AND NITROGEN ON
THE PROPERTIES OF WELDS IN TITANIUM SHEET

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WRIGHT AIR DEVELOPMENT CENTER

NOTICES

THE EFFECTS OF CARBON, OXYGEN, AND NITROGEN ON THE PROPERTIES OF WELDS IN TITANIUM SHEET

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FOREWORD

This report was prepared by the Battelle
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Research and Development Order No. 615-20,
"Welding, Brazing and Soldering of Metals",
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E. Bowman and Dr. H. K. Adenstedt acting as
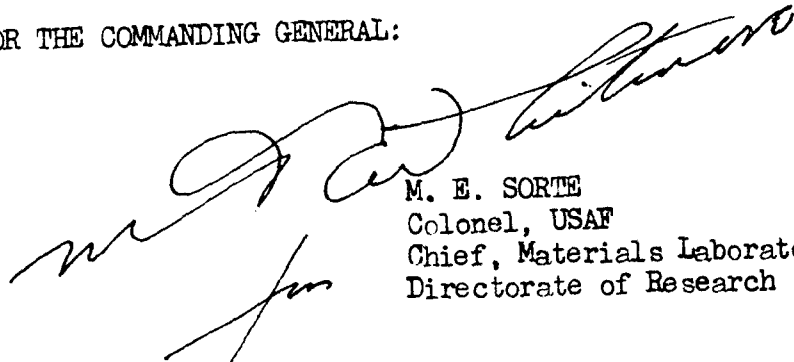project engineers.

ABSTRACT

Three series of titanium alloys were melted and rolled into sheet. The first series included four titanium-carbon alloys with the carbon ranging from 0.13 per cent to 0.74 per cent. The second series contained three titanium-oxygen alloys with the oxygen ranging from 0.15 per cent to 0.55 per cent. The third series had two titanium-nitrogen alloys, one containing 0.13 per cent nitrogen, the other, 0.24 per cent nitrogen. A 0.50 per cent nitrogen alloy was melted but could not be rolled into sheet. Inert-gas-shield arc welds were made in one-sixteenth inch and one-eighth inch sheets of each alloy. Spot welded specimens were made with 0.032 inch and 0.064 inch sheets of each alloy. The physical properties of both arc welds and spot welds in each alloy were determined. The data that was obtained will be useful in establishing the allowable percentages of carbon, oxygen and nitrogen impurties in titanium sheet.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDING GENERAL:

M. E. SORTE
Colonel, USAF
Chief, Materials Laboratory
Directorate of Research

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INTRODUCTION

Titanium and its alloys show promise of assuming an important place as a material of construction in the aircraft industry. To use any structural material in a satisfactory manner, it is necessary to devise practical fabrication methods. One of the fabrication methods which must be understood is the joining of a material both to itself and to other materials. Welding is an important method of fabricating when joining a material to itself and is quite often used for joining one material to another.

Titanium and its alloys can be welded, but the welded joints may not be useful because of low ductility. It has been suggested that low ductility in welded joints is caused by the presence of various elements in the titanium whose basic effect on the weld and heat-affected zone properties are not well understood.

There are many alloying elements which are used with titanium. Some of these are added intentionally, but three which are nearly always present - and perhaps not intentionally - are carbon, oxygen, and nitrogen. Hydrogen may also be present in titanium or titanium alloys but this element was not included in the investigation reported here. All of these elements may be picked up by titanium during melting and fabrication, and in addition oxygen and nitrogen may be introduced into a weld during welding. It has been shown by other investigators that carbon, oxygen, and nitrogen can affect both the strength and ductility of titanium. If present in sufficient quantities, oxygen and nitrogen, in particular, can reduce the ductility of titanium to nearly zero.

Because these three elements are present in most commercial titanium and because it is difficult to prevent their occurrence, the Wright Air Development Center initiated an investigation at Battelle Memorial Institute to study the effects of carbon, oxygen, and nitrogen on the properties of welds and weldments in titanium sheet. The objective of this investigation was to determine what effects carbon, oxygen and nitrogen had on the strengths and ductilities of titanium welds and to determine, if possible, a maximum limit of carbon, oxygen, and nitrogen which could be tolerated in titanium weldments. This report summarizes the results of the investigation.

The investigation was carried out by making inert-gas-shielded tungsten-arc welds and spot welds in sheets of various thicknesses. A range of compositions of titanium-carbon, titanium-oxygen, and titanium-nitrogen alloys was investigated. The strength and ductility properties of weldments in the alloy sheets were compared with the results of studies of the metallurgical structures of welds and heat-affected zones to determine the cause of variations which were found in the various alloys.

SUMMARY

Inert-gas-shielded tungsten-arc welding and spot-welding tests were made on unalloyed iodide and unalloyed sponge titanium sheet. The same types of welding test were also made on titanium-carbon, titanium-oxygen, and titanium-nitrogen-alloy sheets. These alloys were made using sponge titanium. The titanium-carbon alloys included compositions from 0.13 per cent to 0.74 per cent carbon. The oxygen-alloy series included compositions from 0.15 per cent to 0.55 per cent oxygen. The nitrogen-alloy series included compositions from, 0.13 per cent to 0.50 per cent nitrogen. However, the 0.50 per cent nitrogen alloy could not be fabricated into sheet and no welding tests were made on it.

Most of the inert-gas-shielded arc welding was done in a controlled-atmosphere chamber. A few tests were made in the open on the unalloyed sponge sheet using only the gas from the welding torch for shielding and a solid copper bar as a backup. These tests showed that when titanium is welded under these conditions contamination by oxygen and nitrogen may cause high hardness and lowered ductility in the weld. The use of a trailing shield and gas backup would nearly eliminate this contaimination. However, for this investigation it was desirable to reduce the variations caused by air contamination to a minimum and consequently most of the tungsten-arc-welding work was done in the controlled-atmosphere chamber.

The results of welding tests are summarized in Table 1. The properties of welds in iodide sheet and in unalloyed sponge sheet are about the same as the properties of the unwelded base metal. The welds are a little harder and the bend ductilities are not quite so good for the weldments as for the unwelded sheets. Spot welds in both the iodide sheet and the unalloyed sponge sheet have good properties. For equivalent thickness, the tension shear strengths of spot welds in the unalloyed sponge sheet are about the same as can be obtained from spot welds in 90,000 psi ultimate strength stainless steel. Spot welds on both the iodide and sponge sheets have good tension-shear ratios (0.38 to 0.56) as determined by the ratio of the cross-tension strength to the tension-shear strength.

The results of tests on the carbon alloys indicate that up to 0.13 per cent carbon these alloys have good weldability. At some composition level between 0.13 and 0.28 per cent, the carbon begins to have an adverse effect on the ductility of both arc and spot welds. This effect is caused by the precipitation of carbide during the freezing of the weld into a network which is more or less continuous depending on the carbon content. This carbide network is brittle and forms good fracture paths through the structure. At 0.55 per cent carbon, the bend ductility of arc welds is practically zero. Heat treatment will not affect the amount of carbide present in the welds in the high-carbon sheet sufficiently to improve their ductility. The

TABLE 1. SUMMARY OF RESULTS OF TESTS MADE WITH UNALLOYED AND ALLOYED TITANIUM SHEET[1]

Alloyed Sheet Made With Sponge Titanium

Material	Unwelded Sheet — Ultimate Tensile Strength, psi	Yield Strength, psi[2]	Elongation in 2 inches, %	Reduction of Area, %	Minimum Bend Radius[3] Longitudinal	Transverse	Inert Gas-Shielded Arc – Welded Sheet — Ultimate Tensile Strength, psi	Elongation in 2 inches, %	Reduction of Area, %	Minimum Bend Radius[3,4] Longitudinal	Transverse	Spot-Welded Sheet — Tension-Shear Load, lb	Cross-Tension Load, lb	Tension-Shear Ratio[5]
Iodide	43,400	24,000	53	67	<1T	<1T	43,100	34	55	1T	<1T	1,875	1,050	0.56
Sponge (welded in chamber)	66,900	45,700	30	44	<1T	1T	70,800	22	37	3T	2T	–	–	–
Sponge (welded in open)	–	–	–	–	–	–	71,100	19	0	4T	4T	2,400	900	0.37
0.13% carbon	76,200	62,800	34	48	1T	1T	81,700	23	39	4T	3T	2,500	1,500	0.60
0.28% carbon	91,300	77,400	24	33	2T	2T	93,800	24	19	8T	>12T	2,600	800	0.31
0.55% carbon	98,700	76,300	21	33	4T	6T	92,300[7]	2	9	12T	>12T	2,400	300	0.13
0.74% carbon	94,200	78,100	8	12	6T	8T	95,500[7]	1	5	>12T	>12T	1,600	300	0.19
0.15% oxygen[6]	93,400	81,600	23	40	3T	2T	96,000	10	24	3T	2T	2,600	1,200	0.46
0.30% oxygen[6]	111,000	95,200	27	38	3T	8T	101,000	12	15	12T	>12T	2,800	900	0.32
0.55% oxygen[6]	126,000	120,500	3	7	>12T	>12T	103,000[7]	0	2	>12T	>12T	1,250	60	0.05
0.13% nitrogen	112,000	98,300	20	39	3T	4T	113,000	13	16	8T	>12T	2,750	400	0.15
0.24% nitrogen	118,000	113,000	28	4	5T	>12T	120,000[7]	0	0	>12T	>12T	2,100	300	0.14
0.50% nitrogen	Could not be rolled to sheet						–	–	–	–	–	–	–	–

(1) Values for 0.064-inch sheet used since they are reasonably representative.

(2) 0.2% offset yield strength.

(3) Minimum punch radius in terms of sheet thickness around which specimen would bend without cracking. 1T is approximately 33% elongation over short gage length which depends on sheet thickness. 12T is approximately 4% elongation.

(4) All bend specimens failed in weld except those made with the titanium –0.28 per cent carbon alloy which failed in heat-affected zone.

(5) Cross-tension load.
    Tension-shear load.

(6) Estimated oxygen content based on amount added plus estimated oxygen content from sponge and pickup during melting.

(7) Fracture occurred in weld. In all other cases fracture occurred in base metal usually outside of heat affected zone.

properties of spot welds in the carbon alloys, particularly the cross-tension strengths, also deteriorate at some carbon content between 0.13 and 0.28 per cent and for the same reasons. The carbide network occurs in spot welds in higher carbon sheet as well as in arc welds and causes the welds to behave in a brittle manner.

Oxygen begins to have an adverse effect on the properties of welds in titanium at lower concentrations than carbon. Arc welds in titanium containing more than about 0.15 per cent oxygen have low ductility. This low ductility is the result of small cracks which occur in the welds, and the amount of cracking observed increases with increasing oxygen. This cracking is apparently a result of the inherent brittleness of the higher oxygen alloys and probably is caused by shrinkage stresses. Both the tension-shear and cross-tension strengths of spot welds in alloys containing more than 0.30 per cent oxygen are low. The ductilities of spot welds in the high-oxygen alloys are low and again this is apparently a result of the inherently low ductility of titanium containing this much oxygen.

Nitrogen has the most adverse effect upon the weldability of titanium of the three elements studied during this investigation. Arc welds in titanium sheet containing 0.13 per cent nitrogen have very low bend ductility. As in the oxygen alloys, this low bend ductility is caused by cracks which occur in the welds and the base plate adjacent to the welds. However, these cracks appear at much lower alloying levels than with oxygen. When the nitrogen content reaches 0.24 per cent, the arc-welded specimens have no ductility either in bend tests or in tension tests. The deleterious effect of nitrogen is also apparent in spot-welding tests. As with the oxygen alloys, it is most apparent in the cross-tension tests. Spot welds in alloys containing 0.13 per cent nitrogen have about half the cross-tension strength of spot welds in unalloyed sponge titanium sheet. At 0.5 per cent nitrogen, the cross-tension strength is considerably less. The addition of nitrogen does not affect the shear strength of these spot welds as greatly as it does the cross-tension tests. Consequently, the shear ratios of spot welds in nitrogen sheet are very low. Unfortunally the nitrogen alloys used in the tests reported here do not give a complete story of the effect of nitrogen. It is obvious that the 0.50 per cent nitrogen alloy is too high. What is needed to complete the data are some welding tests on an alloy containing from 0.05 to 0.10 per cent nitrogen. Without this, it is possible to say only that 0.13 per cent nitrogen is too high for good weldability without saying what the maximum nitrogen content should be.

The results of this investigation have shown that nitrogen and oxygen in rather small quantities can have very bad effects on both arc and spot welds in titanium. This emphasizes that shielding of titanium from the air during arc welding is very necessary. Shielding of spot welds while they are being made is not so critical because there is much less chance of contamination of the weld by the air.

During this investigation, it has been found that porosity can be a problem in welding titanium. It is believed that porosity in arc welds is caused by hydrogen which may be present as a hydride in the titanium or may be absorbed by the molten pool during welding.

PREPARATION OF TITANIUM SHEET

The materials used in this investigation were arc melted from iodide titanium and from titanium sponge. Both the unalloyed and the alloyed ingots were melted in an arc furnace using a tungsten electrode. The feed material was added during melting as small particles. The iodide crystal bars used were cut into cubes about 1/4 inch square. The sponge titanium was screened to -1/2 inch to +1/8 inch. The titanium sponge was leached in methyl alcohol and heated at 750 F for 2 hours before being used. This treatment was used to remove magnesium chloride and minimize spatter. All melting was done under an atmosphere of 99.93 per cent or better argon. The furnace was purged by evacuating it before filling with argon.

The carbon alloys were made by mixing sponge titanium with the proper amounts of powdered graphite. Mixing was accomplished by tumbling the sponge and the graphite in a rotating mill. The graphite-sponge mixture was double arc melted to produce a homogeneous ingot. Ingots from the first melting were rolled into plate, and the plate was then cut into pieces which were used as feed material for the second melting.

The titanium-oxygen alloys were made by mixing a master alloy and titanium sponge. The master alloy was made by outgassing titanium sponge in a vacuum and then holding the outgassed sponge for four hours at 1380 F. in an atmosphere of pure oxygen. This produced an alloy of 4 per cent oxygen. The master alloy was mixed in proper proportions with titanium sponge and double arc melted to produce homogeneous ingots. Ingots containing nominal weight percentages of 0.10, 0.25, and 0.50 per cent oxygen were made. The oxygen alloys have not been analyzed for oxygen content. The oxygen content of the master alloy was determined by weight gain. The nominal compositions of the oxygen alloy reported were determined by using the calculated composition of the master alloy.

The titanium-nitrogen alloys were also made by arc melting titanium sponge and a master alloy. The titanium-nitrogen master alloy was made by arc melting titanium sponge in an atmosphere of 50 per cent dried nitrogen and 50 per cent high-purity argon. The master alloy was analyzed for nitrogen, and the analytical value was used for determining the amount of master alloy to be added to the arc-melt heats. The titanium-nitrogen alloys were made by double arc melting, and the ingots were analyzed for nitrogen after the second melting.

Table 2 shows the forging and rolling temperature used for fabricating the various unalloyed and alloyed titanium ingots into sheet. With one exception, no difficulty was encountered in forging or rolling the various ingots. The exception was the ingot containing 1/2 per cent nitrogen. This ingot cracked badly during rolling, and no sheet was obtained from this alloy.

TABLE 2. FORGING AND ROLLING TEMPERATURES USED TO FABRICATE TITANIUM SHEETS FROM INGOTS

Alloy	Temperature, F		
	Forging	Rolling to Slab	Rolling Slab to Sheet
Iodide	1450	1450	1250
Unalloyed Sponge (Process A)	1450	1450	1250
Carbon Alloys			
0.13%	1650	1450	1250
0.28%	--	--	--
0.55%	1650	1650	1250
0.74%	1650	1650	1250
Oxygen Alloys			
0.15%	1650	1450	1250
0.30%	1650	1450	1250
0.55%	1800	1650	1250
Nitrogen Alloys			
0.13%	1650	1450	1250
0.24%	1650	1450	1250
0.50%*	1800	1700	1700

*Rolled to 0.132-inch thickness. Impractical to roll to thinner sheet because of severe cracking.

The sheets were hot rolled to 0.003 inch over final thickness. Scale was removed by sand blasting, and the sheets were then cold rolled to final thickness. After being cold rolled, the sheets were annealed in a vacuum for 10 hours at 1250 F. After annealing, the sheets were pickled in a solution of 50 per cent sulphuric acid containing 60 grams of ammonium fluoride per liter of solution. All of the sheets except the 0.50 per cent nitrogen had smooth surfaces and were in excellent condition for welding tests. Radiographs showed that all sheets contained a few tungsten inclusions. The positions of these inclusions were determined from the

radiographs, and the inclusions were either cut out of the sheet or test specimens were taken so that they did not include the inclusions.

The filler metals used in all of the tests were sheared from the finished sheet.

The compositions and hardnesses of the various sheets produced are shown in Table 3.

TABLE 3.   COMPOSITIONS AND HARDNESSES OF TITANIUM SHEET

Alloy, Nominal Composition	Actual Composition, weight per cent	Average Hardness, Vickers
Iodide	(1)	101
Sponge	(2)	161
Carbon Alloys		
0.10%	0.13	177
0.25%	0.28	253
0.50%	0.55	243
0.75%	0.74	238
Oxygen Alloys		
0.10%	0.15[3]	233
0.25%	0.30[3]	264
0.50%	0.55[3]	323
Nitrogen Alloys		
0.10%	0.13	239
0.25%	0.24	278

(1) Carbon 0.03%, nitrogen 0.004%

(2) Carbon 0.03-0.09%, nitrogen 0.005-0.01%, oxygen estimated at 0.05% from strength of unalloyed sheet and amount of nitrogen present.

(3) These figures were arrived at by adding the estimated amount of oxygen in the unalloyed sponge sheet to the amount of oxygen added during melting through the oxygen master alloy.

WELDING PROCEDURES

Two types of welding were used in this investigation. Arc-welding tests were made on sheets 0.064 inch and 0.125 inch thick. Spot-welding tests were made on sheets 0.032 and 0.064 inch thick.
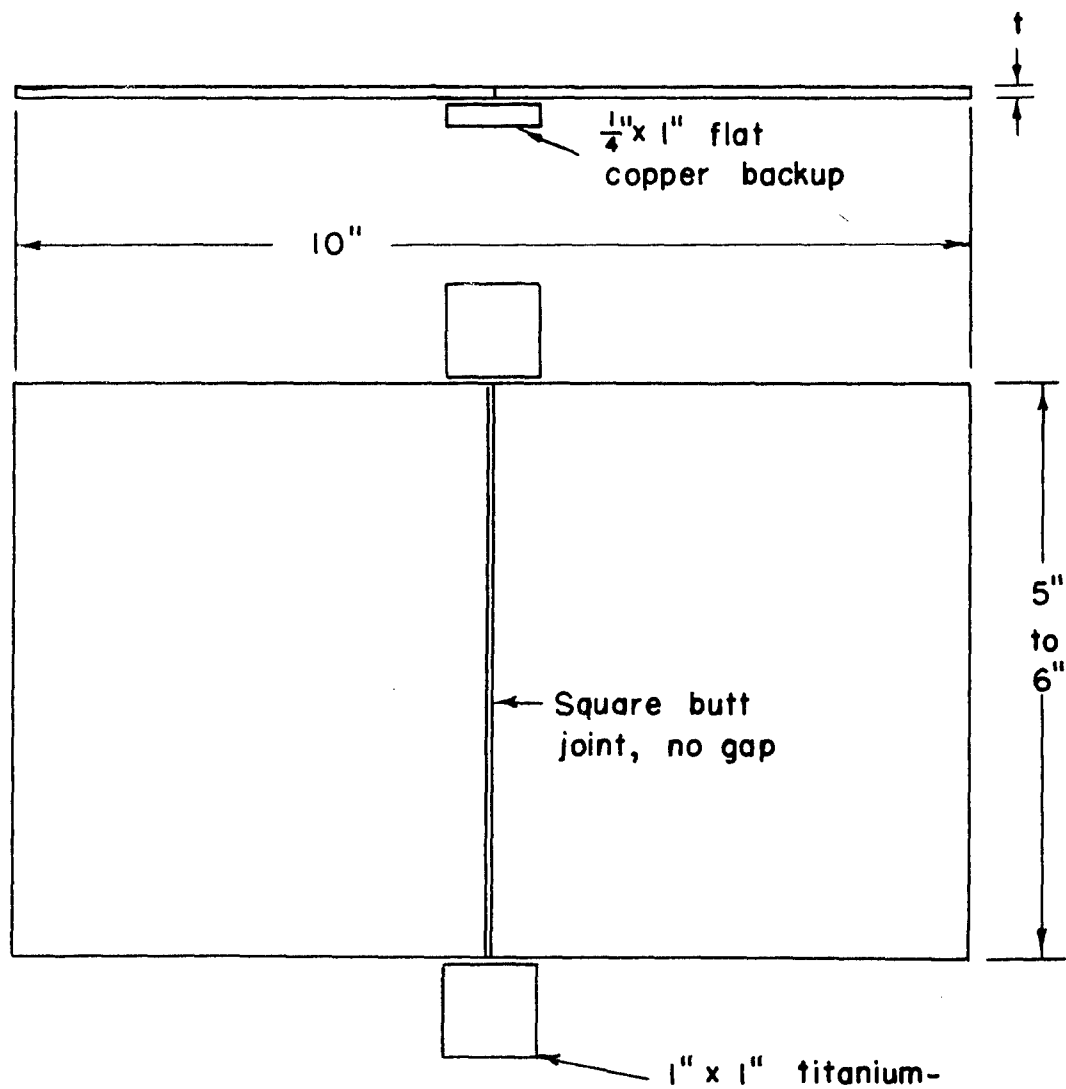
Arc Welding

The inert-gas-shielded tungsten-arc-welding process was used for all of the arc-welding tests made during this investigation. A standard tungsten-arc torch was used. In all tests, the electrode used was 1/16 inch in diameter, and high-purity (99.94 per cent) argon was used for shielding. All welding was done using straight-polarity direct current. Arc welding on 0.064-inch sheet was done with an arc voltage of 12 to 14 volts and a welding current of 55 to 65 amperes. On 0.125-inch sheet, the arc voltage was 15 to 17 volts, and the welding current was 100 to 110 amperes. The welds produced by these currents were rather wide but full penetration was obtained in nearly all of the welds. The welding speeds used varied for the different sheet thicknesses and were sometimes varied between different lots of sheet to try to eliminate porosity. The details of the specimens used in the arc-welding tests are shown in Figure 1.

Some arc-welding tests were made using only the gas from the torch as a shield. Others were made in the controlled atmosphere chamber shown in Figure 2. This chamber is purged by evacuating it to low pressures and then admitting the shielding gas desired until a small positive pressure is reached.

Spot Welding

A 200-kva, 60-cycle, 3-phase, alternating-current, frequency-converter-type spot welder was used for all of the spot-welding tests. Figure 3 is a photograph of this spot welder. The electrodes used for welding were made from materials corresponding to RWMA Class 1. The electrodes were 5/8 inch in diameter and were water cooled. The tips of the electrodes had a 3-inch spherical radius face.

The types of spot-welding specimens used are shown in Figure 4.

Figure I. DETAILS OF SPECIMEN USED FOR ARC-WELDING TESTS
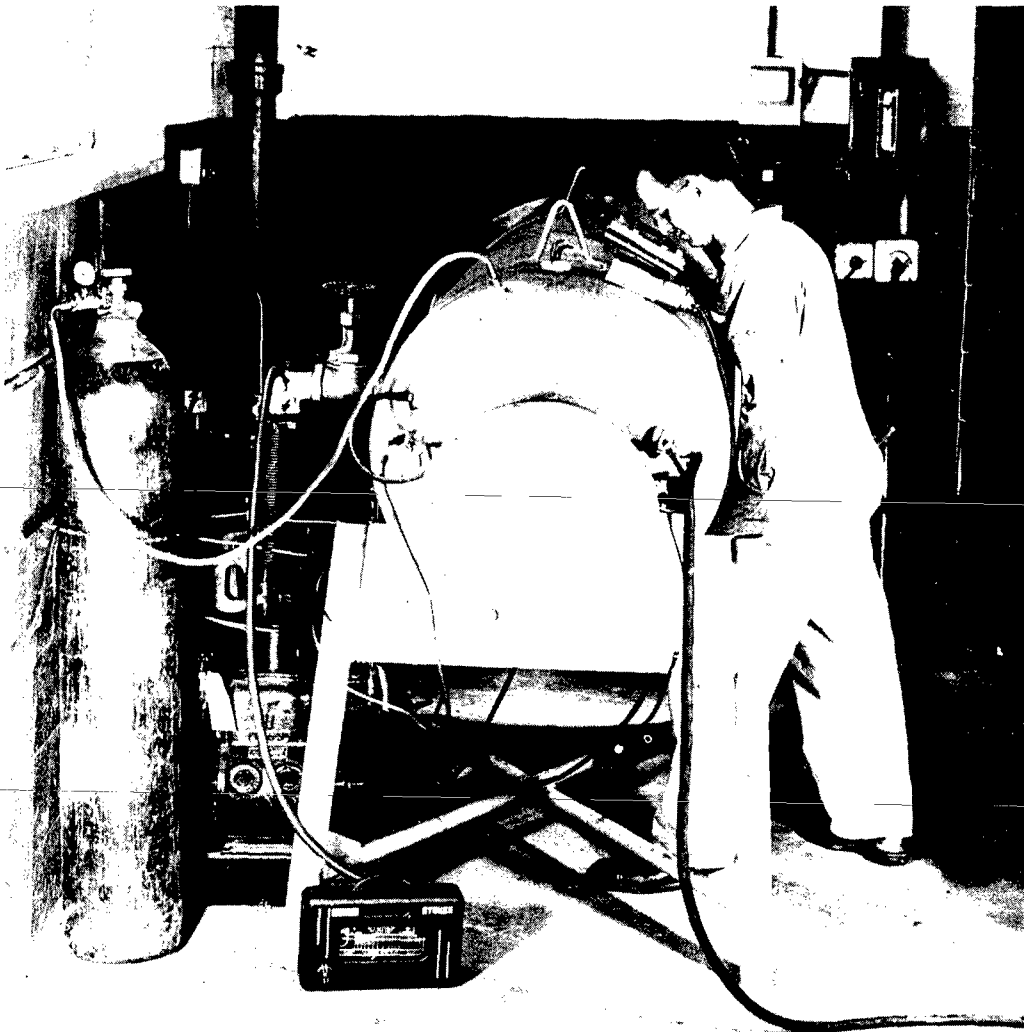
Note: t= 0.064" or 0.125"

FIGURE 2. CONTROLLED-ATMOSPHERE CHAMBER USED IN ARC-WELDING TESTS
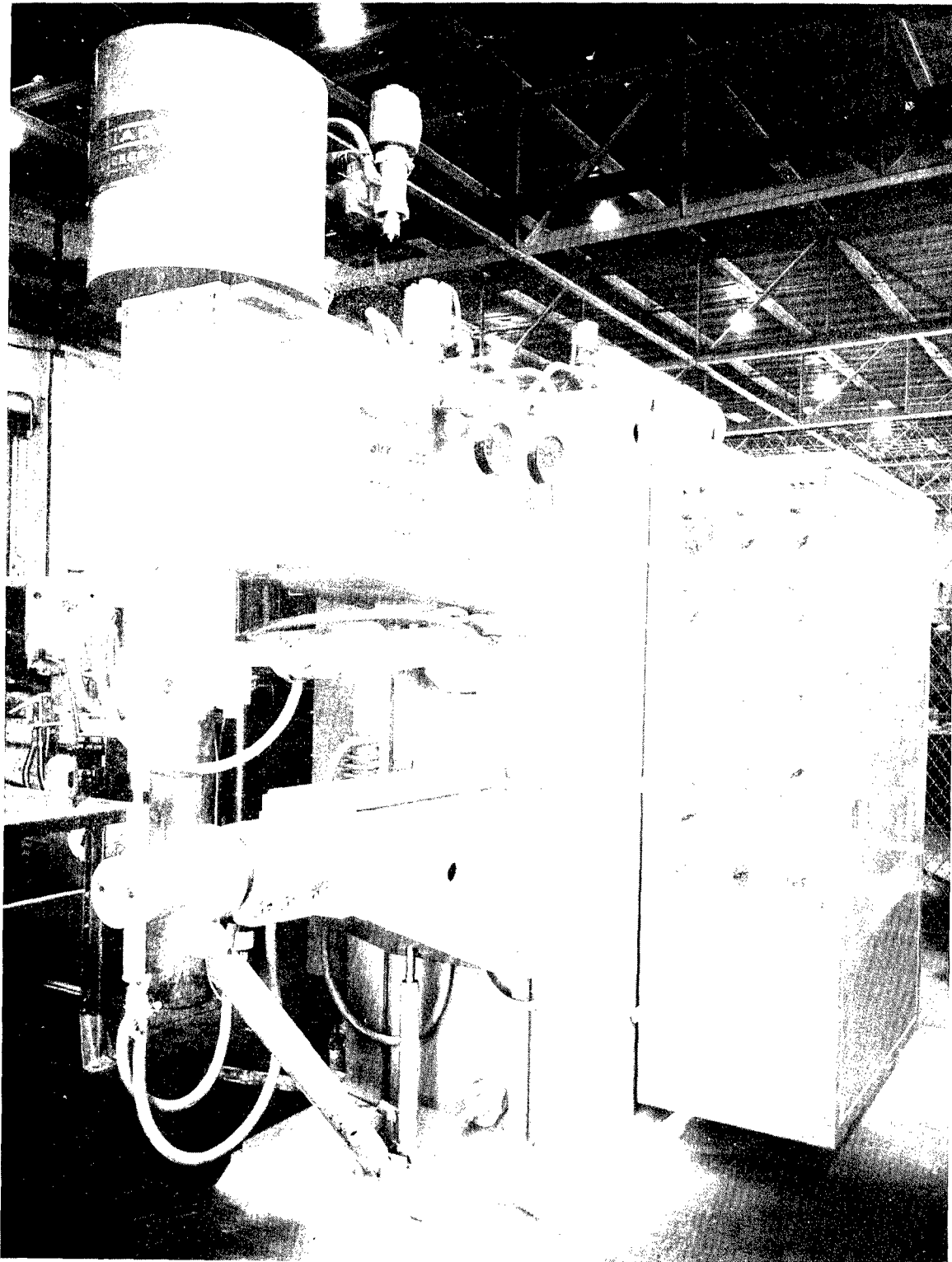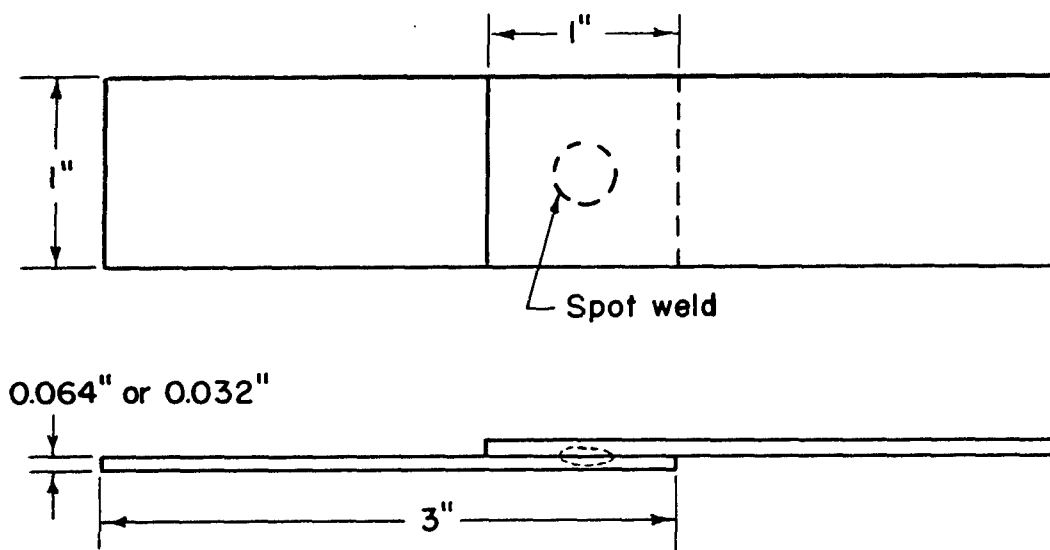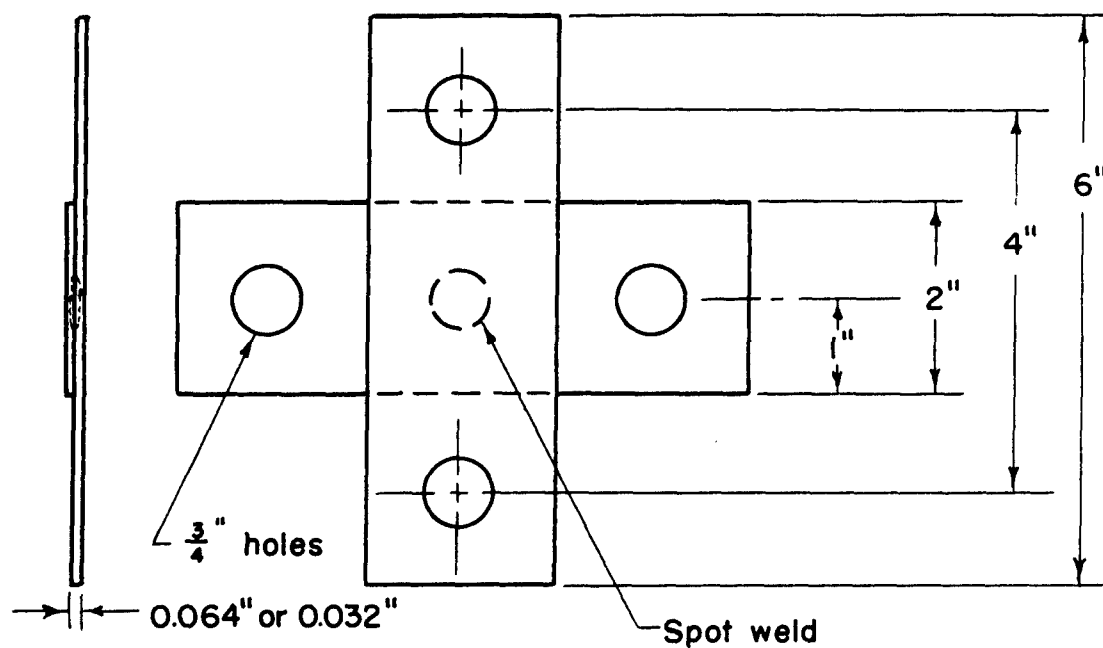
FIGURE 3.   200-KVA, 60-CYCLE FREQUENCY-CONVERTER SPOT WELDER USED IN SPO
WELDING TESTS

Tension-Shear Test Specimen — Full scale

Cross-Tension Test Specimen — Half scale

Figure 4.   DETAILS OF TENSION-SHEAR AND CROSS-TENSION
TEST SPECIMENS

The spot-welding conditions used in all spot-welding tests are shown in the following tabulation:

	0.032-Inch Sheet	0.064-Inch Sheet
Tip force, pounds	600	1,200
Approximate welding current, amperes	21,000-24,000	25,000-27,000
Number of impulses	1	2
Duration of impulse, cycles	5	5
Off time, cycles	-	1

A large number of tests showed that these conditions consistently produced high weld strengths in the titanium sheet. The higher amperages were used with the alloy sheets containing the larger amount of alloying elements. In all tests, the conditions were adjusted to produce spots which had diameters of 3 to 5 times the thickness of the sheet.

PREPARATION OF TEST SPECIMENS

The tests made on the unwelded and arc-welded sheets included tension tests, longitudinal bend, and transverse bend tests. Figure 5 shows the details of the specimens used for these tests. The tension specimens were machined to conform with Military Specification MIL-T-5021.

Strain gages (SR-4 Type A-1) were used on the tension specimens cut from unwelded sheet to determine the yield strength of the sheet. The specimens were also scribed with 2-inch gage lengths which were used to determine elongations.

The 1-inch width was selected for the bend specimens, because it provided sufficient width to include all of the weld metal and heat-affected zone in the welded bend specimens.

Testing Procedure

The tension test specimens were tested in a Baldwin Southwark testing machine. Initial rate of loading was 0.03 inch per minute. Shortly after the observations indicated that the yield had been reached, the rate was decreased to allow accurate reading of deflection on a Baldwin Southwark strain indicator. The values for the tension test results given in the tables are averages for three to five specimens.

Tension Specimen

Longitudinal-Bend Specimen

Edges of all bend specimens rounded

Base-Metal Transverse-Bend Specimen

Welded Transverse-Bend Specimen
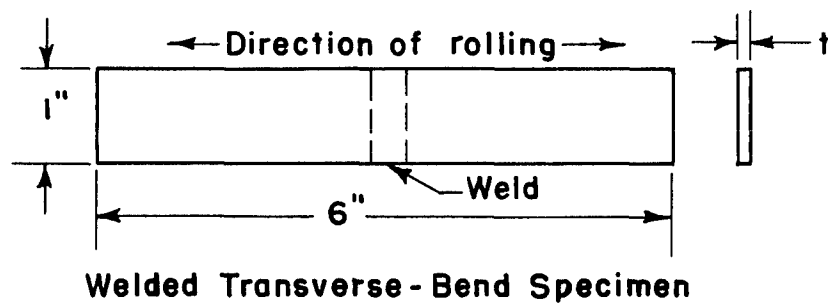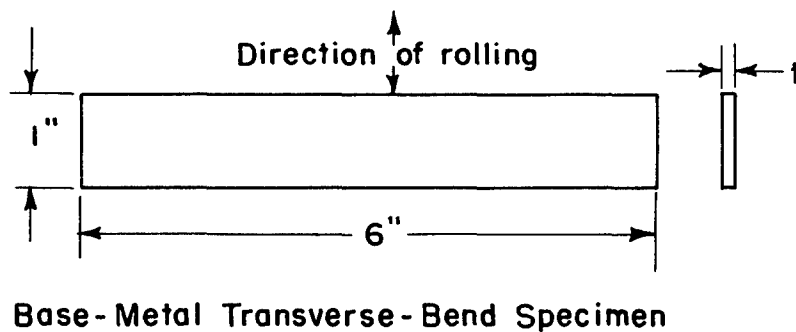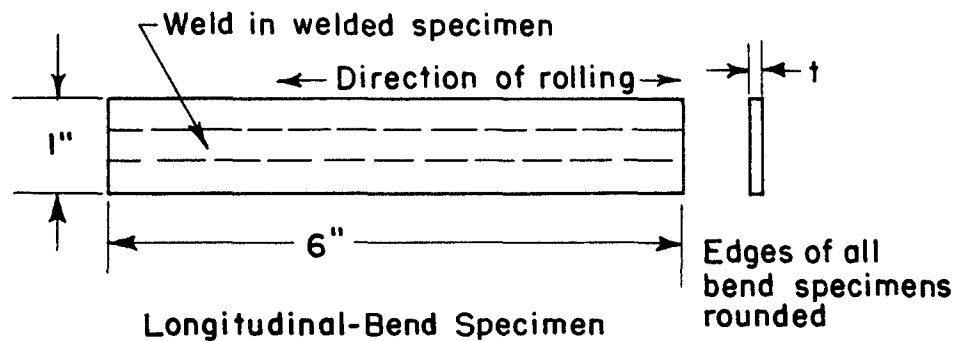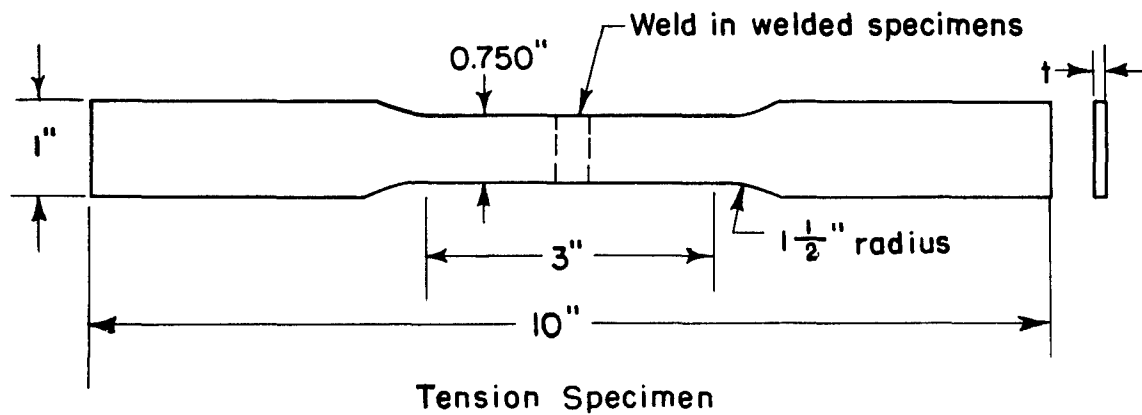
Note: t = 0.032", 0.064", or 0.125"

Figure 5.   DETAILS OF TENSION, LONGITUDINAL-BEND, AND
TRANSVERSE - BEND SPECIMENS

The bend specimens were tested by placing them on a bend die and using punches of various nose radii to bend the specimens. A series of dies with nose radii from 1-1/2 inches to a sharply machined edge were used. The bend-test results are reported in terms of the minimum die radius to which the specimen bent before a crack occurred. To make it possible to compare the ductility of the various thicknesses of sheet, the minimum die radii are reported in terms of sheet thickness. This method of reporting is used because a 2T bend, for example, denotes about the same elongation in the outermost fibers for all sheet thicknesses. The values for bend-test results given in the tables are averages for 5 to 10 specimens.

Tests of Spot Welds

Spot-welded specimens were tested in tension shear and in cross tension. The specimens used for these tests are shown in Figure 4. The tension-shear specimens were tested by pulling them in a tension machine without making corrections for the bending moment introduced by the non-linear loading of the specimen. The tension specimen was tested using the jig shown in Figure 6. The strength values given for spot welds in the tables are averages for 5 to 10 specimens.

Hardness and Metallographic Specimens

Hardness tests were made on specimens cut from arc welds and spot welds. These same specimens were also used for metallographic studies. The specimen was cut so that it contained weld metal, heat-affected zone on both sides of the weld metal, and unaffected base metal on both sides of the heat-affected zones. These specimens were mounted and polished metallographically. After the metallographic examination was completed, hardness surveys were made on the specimens.

PROPERTIES OF UNWELDED SHEET

The strength properties of all of the alloyed and unalloyed sheets used in this investigation were determined, and their metallurgical structures were studied.

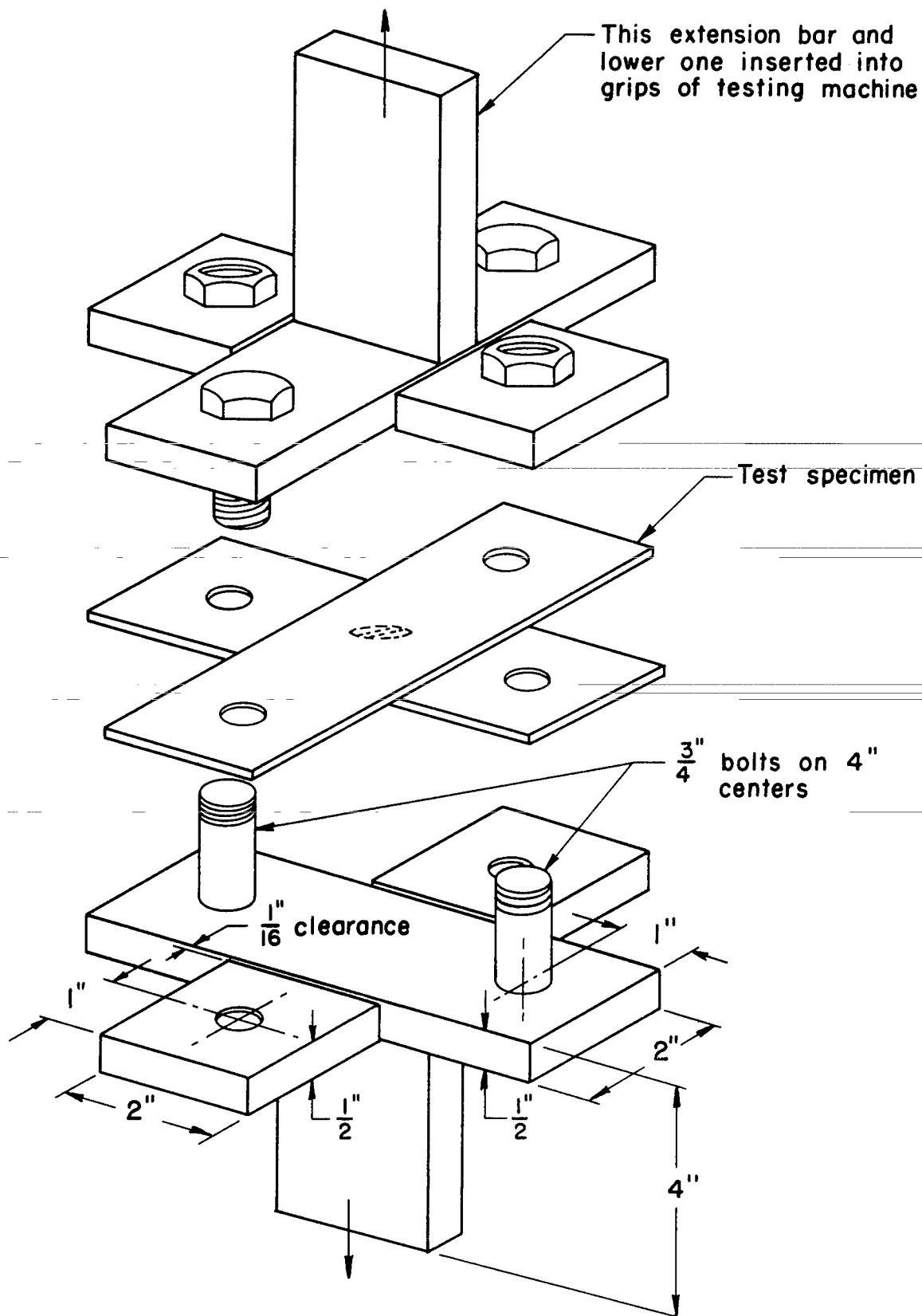This extension bar and
lower one inserted into
grips of testing machine

Test specimen

$\frac{3}{4}"$ bolts on 4"
centers

$\frac{1}{16}"$ clearance

1"

1"

2"

1"

2"

$\frac{1}{2}"$

$\frac{1}{2}"$

4"

FIGURE 6.   JIG FOR CROSS - TENSION TESTS

The tensile and bend properties obtained on all of the sheet used in this investigation are given in Table 4. The comparison of the properties obtained from the alloys used in this investigation with those obtained from alloys made with iodide titanium is shown in Figure 7. The strengths of the sponge alloys are higher than those of the iodide alloys, but this is to be expected. The sponge itself contains some carbon, oxygen, and nitrogen, and from Table 4 it can be seen that the properties of the unalloyed sheet produced from sponge are considerably higher than the properties of the sheet produced from unalloyed iodide titanium. In general, the strength and ductility of each sponge alloy differ from the strength and ductility of the comparable iodide alloy by a consistent amount.

It can be easily seen from consideration of the data given in Table 4 and Figure 7 that oxygen and nitrogen have a much greater effect upon the properties of titanium than does carbon. This is particularly true with respect to ductility. In alloys of oxygen and nitrogen, the ductility drops off rapidly as the amount of alloying element increases. At a rather low level, the ductility becomes nearly zero. With carbon, the ductility drops off somewhat, but does not become zero.

Structures of Base Plate

The structures of the iodide and Process A sheets in the rolled and stress-relieved condition consist of rather small equiaxed alpha grains. The 0.13 per cent carbon alloy has a structure which also consists of equiaxed alpha grains. However, in the 0.25 per cent carbon alloy a few equiaxed carbide particles can be found. In the 0.55 and 0.75 per cent carbon alloys, there is quite a bit of the equiaxed carbide to be found in the microstructure. All of the oxygen and nitrogen alloys have equiaxed alpha structure in the rolled and stress-relieved condition. The structures of the rolled and annealed sheets are shown in Figures 8 and 9.

TABLE 4. STRENGTH PROPERTIES OF UNALLOYED AND ALLOYED TITANIUM SHEET

Composition	Sheet Thickness, in.	Yield Strength, psi, 0.2% offset	Tensile Strength, psi	Elongation in 2 in., per cent	Reduction of Area, per cent	Minimum Bend Radii(1)		Average Hardness, Vickers
						Longitudinal	Transverse	
Iodide	0.064	24,000	43,400	53	67	<1T	<1T	101
Unalloyed Sponge (Process A)	0.032	46,400	67,200	34	43	1T	1T	161
	0.064	45,700	66,900	30	44	1/2T	1T	
	0.125	45,100	66,700	35	46	1-1/2T	4T	
0.13% Carbon	0.032	55,900	74,000	31	42	1-1/2T	1-1/2T	177
	0.064	62,800	76,200	34	48	1T	1T	
	0.125	61,900	75,700	33	44	2T	1-1/2T	
0.28% Carbon	0.032	74,800	89,200	28	37	2T	2T	253
	0.064	77,400	91,300	24	33	2-1/2T	1-1/2T	
	0.125	77,000	90,800	24	33	3T	2T	
0.55% Carbon	0.032	75,000	89,000	11	21	3T	2T	243
	0.064	76,300	98,700	21	33	4T	6T	
	0.125	72,600	90,100	20	33	2T	4T	
0.74% Carbon	0.032	93,400	110,600	7	5	6T	8T	238
	0.064	78,100	94,200	8	12	6T	8T	
	0.125	92,000	95,700	10	21	4T	4T	
0.15% Oxygen	0.032	79,300	91,700	22	41	3T	2T	233
	0.064	81,600	93,400	23	40	3T	2T	
	0.125	84,000	92,700	26	40	2T	2T	
0.30% Oxygen	0.032	90,000	107,000	24	36	6T	4T	264
	0.064	95,200	110,900	27	38	3T	8T	
	0.125	99,200	111,300	25	38	12T	12T	

TABLE 4. (Continued)

Composition	Sheet Thickness, in.	Yield Strength, psi, 0.2% offset	Tensile Strength, psi	Elongation in 2 in., per cent	Reduction of Area, per cent	Minimum Bend Radii(1) Longitudinal	Transverse	Average Hardness, Vickers
0.55% Oxygen	0.032	124,300	134,000	25	33	> 12T	> 12T	323
	0.064	120,500	126,000	3	7	> 12T	> 12T	
	0.125	121,700	131,000	8	10	> 12T	> 12T	
0.13% Nitrogen	0.032	92,000	105,000	26	40	2T	3T	239
	0.064	98,300	112,000	20	39	3T	4T	
	0.125	95,500	106,000	21	32	4T	6T	
0.24% Nitrogen	0.032	111,000	118,000	19	5	3T	> 12T	278
	0.064	113,000	118,000	28	4	5T	> 12T	
	0.125	--	127,000	0.5	4	> 12T	> 12T	
0.50% Nitrogen	Could not be rolled to desired sheet thickness.							384

(1) Minimum punch radius over which sheet could be bent without cracking. T = sheet thickness; 1T is about 30% elongation, 12T is about 4% elongation.

Figure 7. COMPARISON OF STRENGTH AND ELONGATION OF ALLOYS MADE WITH SPONGE TITANIUM AND ALLOYS MADE WITH IODIDE TITANIUM
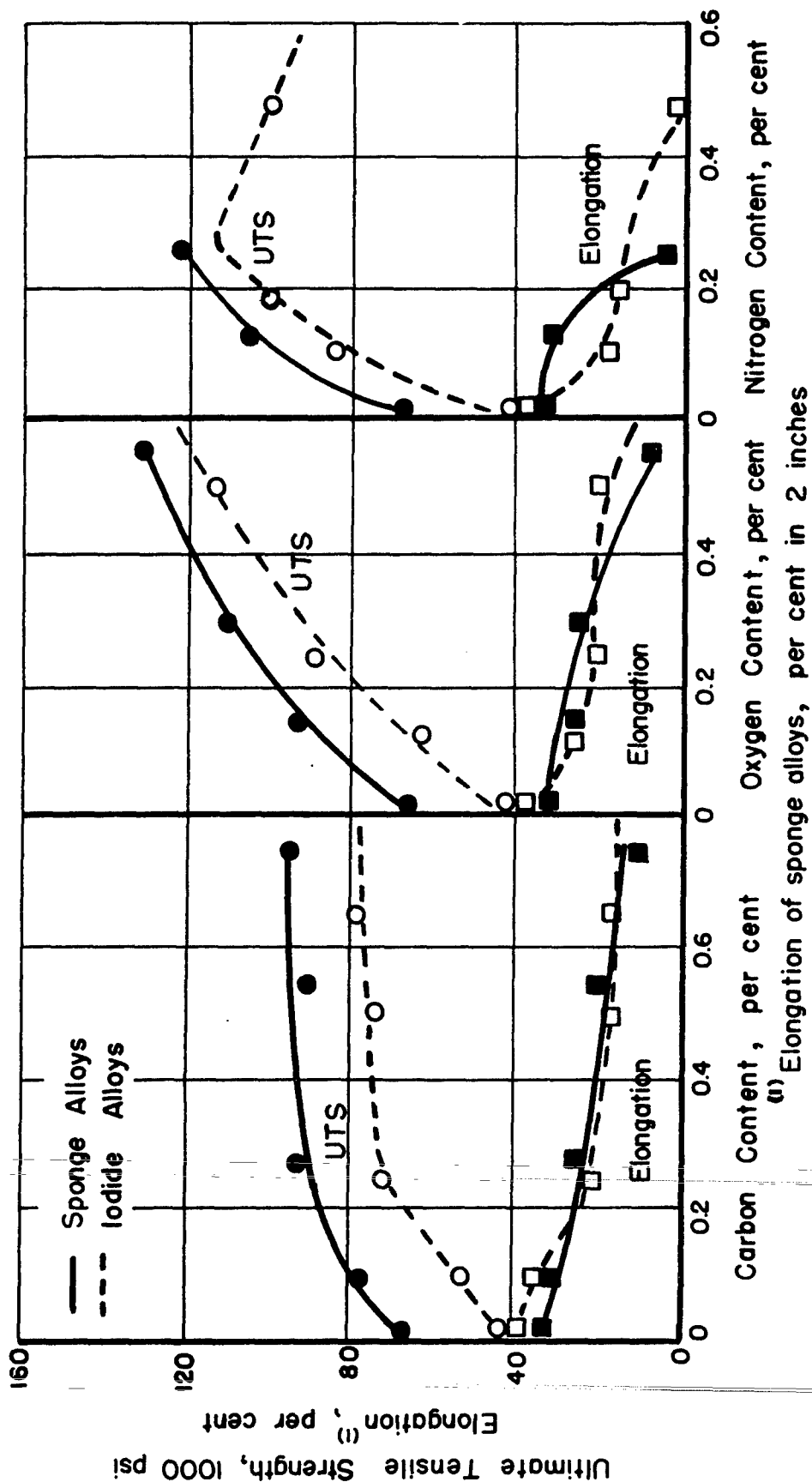
Note: Iodide data from "Alloys of Titanium with Carbon, Oxygen, and Nitrogen," by R.I. Jaffee, H.R. Ogden, and D.J. Maykuth, Journal of Metals, Transactions AIME, Vol. 188, October, 1950, pp 1261-1266

FIGURE 8. TYPICAL ANNEALED
STRUCTURE OF TITANIUM
SHEET USED IN THIS INVESTI-
GATION EXCEPT THOSE CON-
TAINING 0.28 PER CENT OR
MORE CARBON.
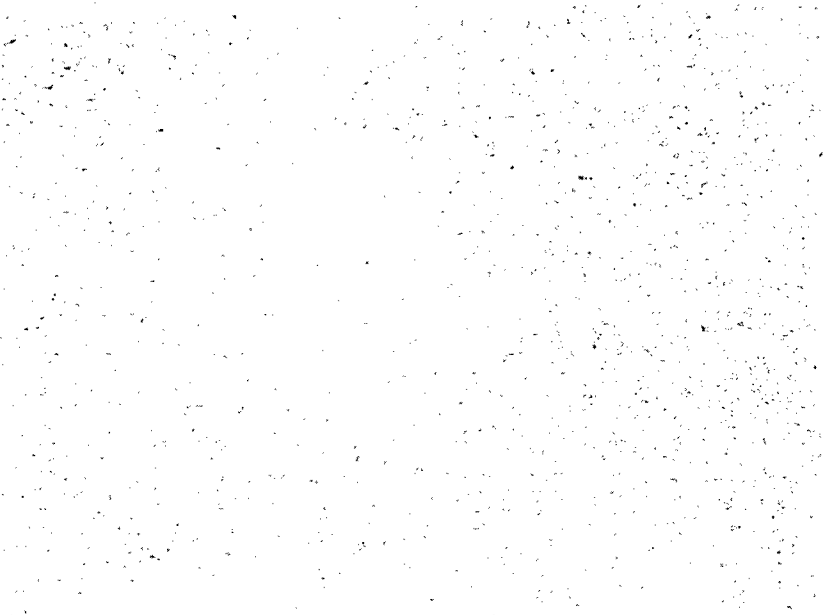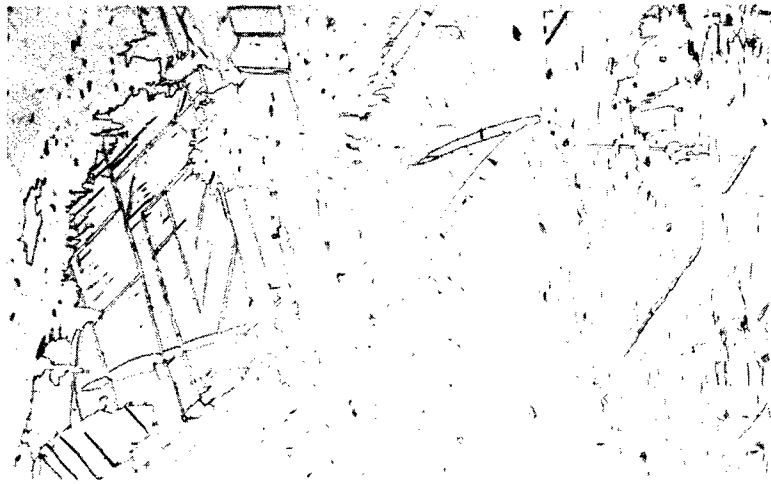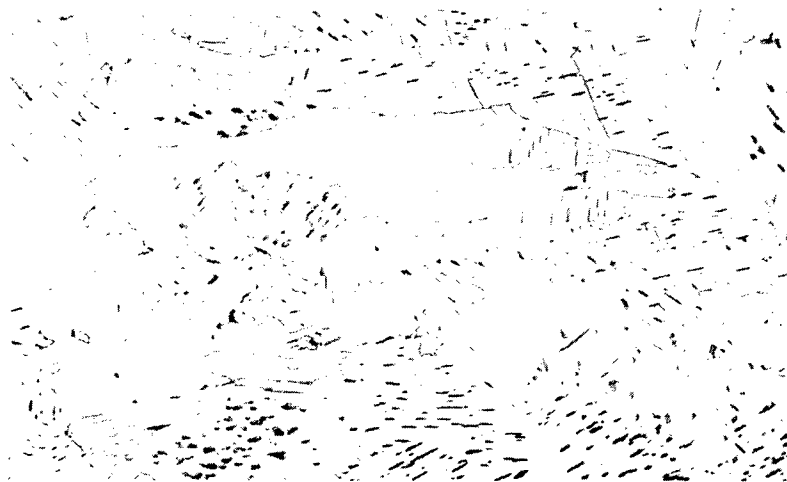
Dark line markings are
titanium hydride

FIGURE 9. TYPICAL ANNEAL-
ED STRUCTURE OF TITANIUM
SHEET USED IN THIS INVESTI-
GATION CONTAINING 0.28
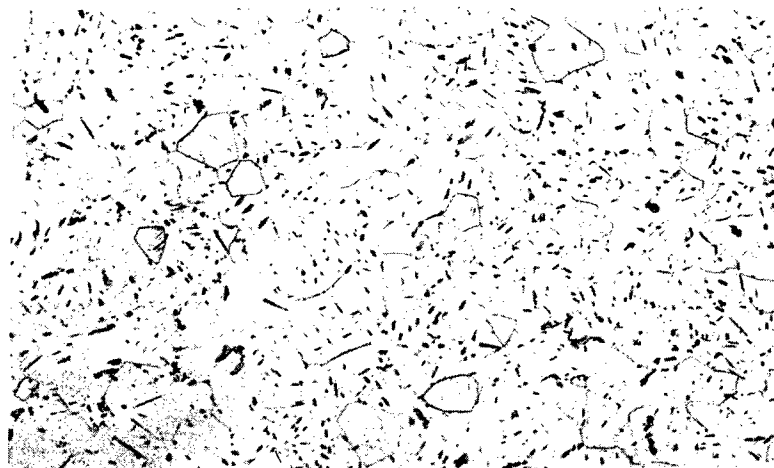PER CENT OR MORE CARBON.

Gray equiaxed constituent
is carbide. Photomicrograph
is of 0.74 per cent carbon
alloy

Weld

Heat-Affected Zone

Unaffected Base Plate

FIGURE 10. STRUCTURES FOUND IN DIFFERENT ZONES OF
ARC WELD IN IODIDE TITANIUM SHEET

PROPERTIES OF WELDMENTS IN TITANIUM

Unalloyed Iodide Titanium

The properties of arc welds in the iodide titanium sheets are given in the following tabulation:

	Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation in 2 inches, per cent	Reduction of Area, per cent	Minimum Bend Radius	
					Longitudinal	Transverse
Unwelded	24,000	43,400	53	67	$<$ 1T	$<$ 1T
Welded	--	43,100	34	55	1T	$<$ 1T

Properties of the unwelded sheet are included for comparison. It can be seen from this tabulation that there is little difference between the properties of the iodide titanium weldments and the unwelded sheet. The welds are somewhat stronger than the base metal, and fractures in the welded tension specimens occur in the base metal. Because of this, the elongation over 2 inches is somewhat lower for the welded specimens than for the unwelded specimens. This was found to be true for all of the transverse tensile specimens tested during this investigation except those which were very brittle and fractured through the weld. The results of the bend tests indicate that the ductility of the weld itself in the iodide sheet is approximately the same as the ductility of unwelded sheet.

The structures present in the welded sheet are shown in Figure 10. As can be seen from this figure, the weld consists of rather large alpha grains. That portion of the heat-affected zone which has been heated above the alpha-to-beta transformation temperature also consists of large alpha grains. The acicular alpha which appears in the welds is probably caused by oxygen contamination during welding. This is the type of Widmanstätten precipitation which forms the so-called "basket weave" structure in titanium. In the weld shown in Figure 10, the contamination has been very slight. The hardness of this weld was only 10 VHN higher than that of the sheet.

The properties of spot welds in the 0.064-inch iodide titanium sheet are given in the following tabulation:

> Tension-Shear Strength, pounds - 1875
> Cross-Tension Strength, pounds - 1050
> Tension-Shear Ratio - 0.56
> Maximum Vickers Hardness in Weld - 133

These values were obtained from specimens having 3 T spot diameters. (T is sheet thickness.)

Unalloyed Process A Titanium

The properties of arc welds in unalloyed Process A titanium sheet are given in Table 5. The results of tests made on the Process A sheet in the controlled- atmosphere chamber show that there is little difference between the properties of the arc weldments and the unwelded sheet. Again, the tensile ductilities of the arc-welded specimens were somewhat lower than those of unwelded sheet, but this was due to the method of failure of the sheet. Necking down and failure occurred outside of the weld, and, consequently, this reduced the over-all elongation in 2 inches in the specimen. The bend-test results indicate that there is no great difference between the ductility of the weld and that of the unwelded sheet.

For those welds made in the open air, the story is somewhat different. Here, contamination by oxygen and nitrogen during welding has affected the properties of the weldment. As can be seen from Table 5, the bend ductilities of weldments made in the open air are lower than those of weldments made in the controlled-atmosphere chamber. They are also lower than the bend ductility of unwelded sheet.

The properties of spot welds in the unalloyed Process A titanium sheet are given in the following tabulation:

Sheet Thickness, inch	Spot Diameter	Tension-Shear Strength, lb	Cross Tension Strength, lb	Tension-Shear Ratio	Maximum Hardness, Vickers
0.032	5T	1090	445	0.41	220
0.064	3T	2400	900	0.37	222

As was the case with the spot welds in the iodide sheet, the spot welds in the sponge sheet appear to have considerable ductility. The ratio of tension-shear to cross-tension tests is fairly high, and this is some indication both of good ductility and low notch sensitivity.

The metallographic structures of both arc and spot welds made in the unalloyed Process A titanium sheet were not much different from those that were found in the iodide sheet. Both weld and heat-affected zones in the un-alloyed sponge sheet contain more of the alpha structure, which is known as "basket-weave" structure, than welds in iodide sheet. This basket-weave structure can be caused by oxygen and is probably indicative of the difference in purity between the Process A titanium and the iodide titanium. Figure 11 shows cross sections of spot welds in the Process A titanium sheet. The
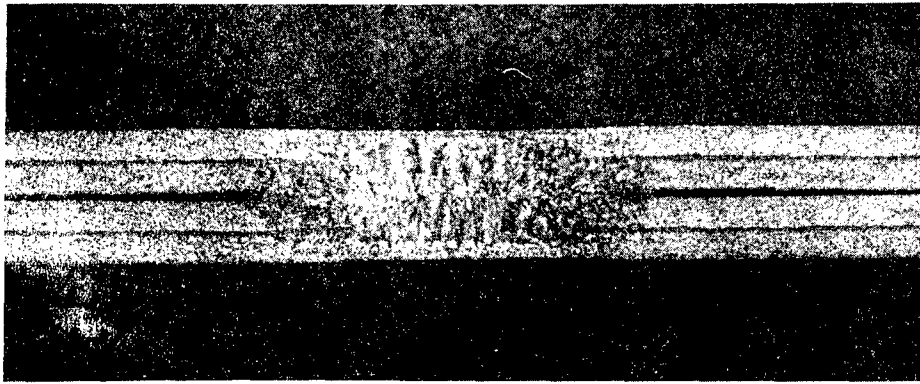
0.032-Inch Sheet
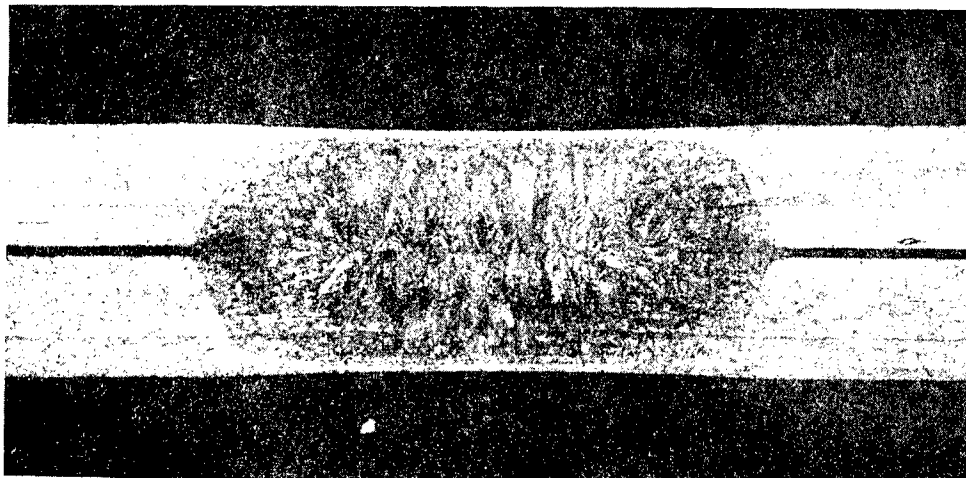
0.064-Inch Sheet

FIGURE 11. CROSS SECTIONS OF SPOT WELDS IN 0.032-
AND 0.064-INCH UNALLOYED SPONGE TITA-
NIUM (PROCESS A) SHEET

TABLE 5. STRENGTH PROPERTIES OF ARC WELDS IN UNALLOYED SPONGE TITANIUM SHEET

Type of Titanium	Sheet Thickness, in.	Tensile Strength, psi	Elongation in 2 in., per cent	Reduction of Area, per cent	Minimum Bend Radii		Maximum Hardness, Vickers
					Longitudinal	Transverse	
Sponge (Process A) Welded in Argon Chamber	0.064	70,800	22	37	3T	1-1/2T	209
	0.125	69,500	21	41	1-1/2T	2T	210
Sponge (Process A) Welded in Air	0.064	71,100	19	40	4T	4T	256
	0.125	68,000	23	44	12T	4T	222

TABLE 6. STRENGTH PROPERTIES OF ARC WELDS IN SPONGE TITANIUM-CARBON-ALLOY SHEET

Composition	Sheet Thickness, in.	Tensile Strength, psi	Elongation in 2 in., per cent	Reduction of Area, per cent	Minimum Bend Radii		Maximum Hardness, Vickers
					Longitudinal	Transverse	
Unalloyed Sponge (Process A)	0.064	70,800	22	37	3T	1-1/2T	209
	0.125	69,500	21	41	1-1/2T	2T	210
0.13% Carbon	0.064	81,700	23	39	4T	3T	235
	0.125	76,900	19	41	2T	4T	243
0.28% Carbon	0.064	93,800	24	19	8T	> 12T	251
	0.125	98,700	19	36	4T	12T	251
0.55% Carbon	0.064	92,300	2	9	12T	> 12T	242
	0.125	90,600	3	3	> 12T	> 12T	274
0.74% Carbon	0.064	95,500	1	2	> 12T	> 12T	260
	0.125	92,600	1	5	> 12T	> 12T	285

thing which is most noticeable in this macrograph is the extent of penetration of the welds. This has been noticed by other investigators[1] and apparently is to be expected when spot welding titanium. These cross sections are typical of spot welds in all of the alloys.

Properties of Welded Titanium-Carbon Alloys

The properties of arc welds in alloys of titanium and carbon are given in Table 6. The properties of the arc weldments in alloys containing 0.13 per cent carbon are about the same as those of the unwelded alloy sheet. However, for alloys containing more than 0.13 per cent carbon, the properties of the arc-welded specimens differ considerably from those of the unwelded sheet.

The 0.25 per cent carbon weldments have about the same tensile properties as do the unwelded sheet. However, the bend-test results for weldments in this alloy differ somewhat from the bend-test results for unwelded sheet. The fracture occurs at lower elongations in the welded sheet than in the unwelded sheet. In addition, this sheet was the only one tested in which fracture in the bend test occurred in the heat-affected zone rather than in the weld.

In the alloys containing 0.55 and 0.74 per cent carbon, both the tensile and bend properties are different in the weldments than in the unwelded sheet. The tensile strength is about the same for the weldments, but the ductility has been greatly reduced by welding. This reduction in ductility is also shown in the bend tests, and a comparison of the bend ductilities of welded and unwelded sheets shows this very definitely. Such a comparison is given in Figure 12.

The cause of the embrittlement of the higher carbon alloys is the formation of a carbide network in the weld during freezing. Hitchcock and Mahla have also related brittleness at high carbon contents with the occurrence of the carbide[2].

The photomicrograph in Figure 13 shows the carbide structure which was found in an arc weld in 0.74 per cent carbon-alloy sheet. The change in equiaxed carbide inclusions which are present in the unaffected base metal and heat-affected zone of a weld to the network which is present in
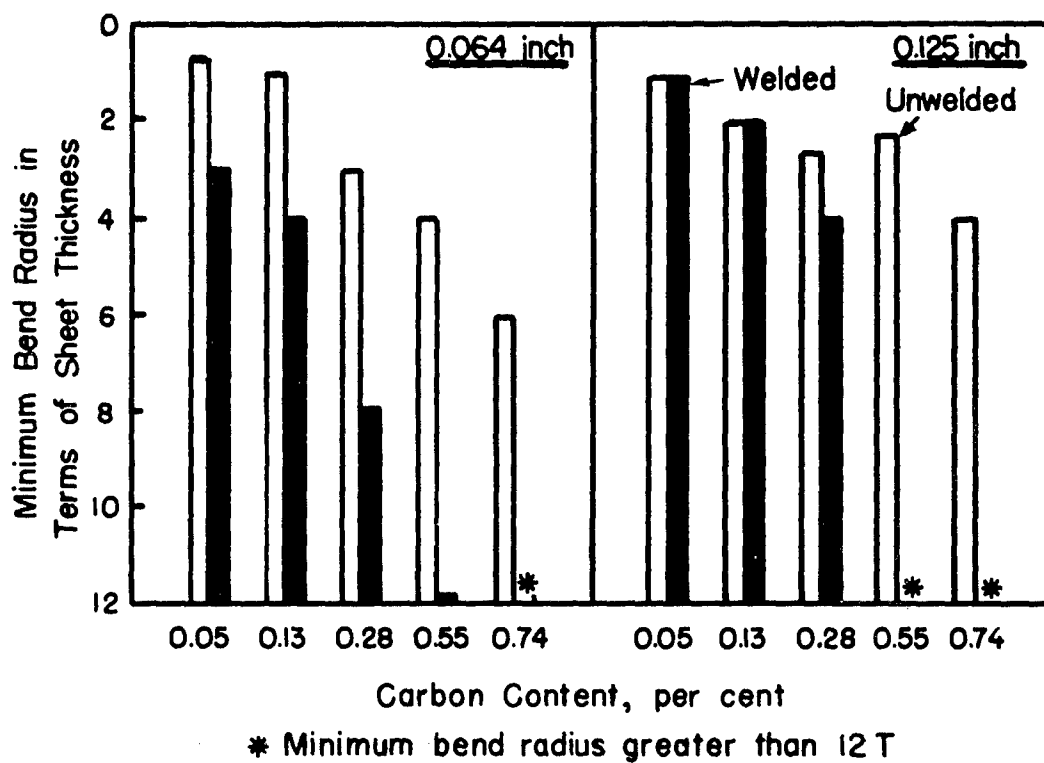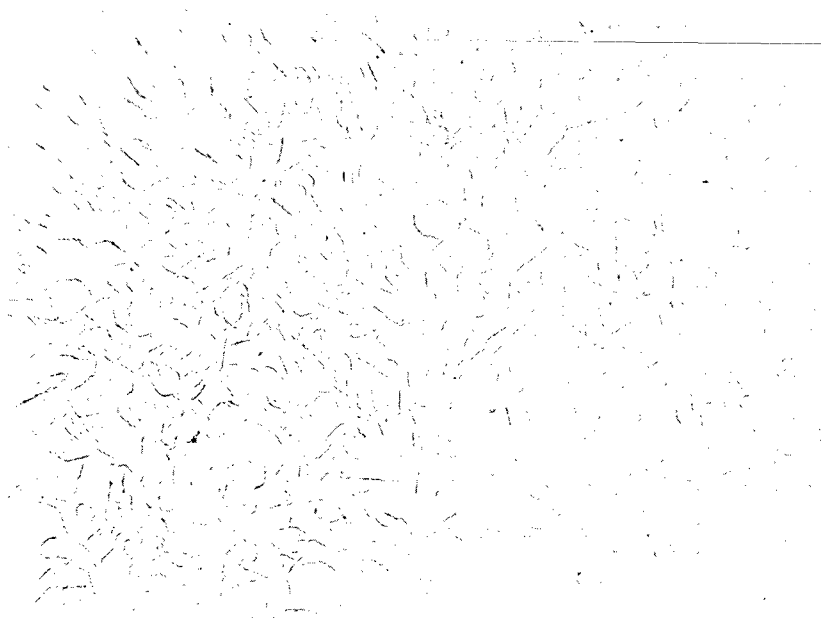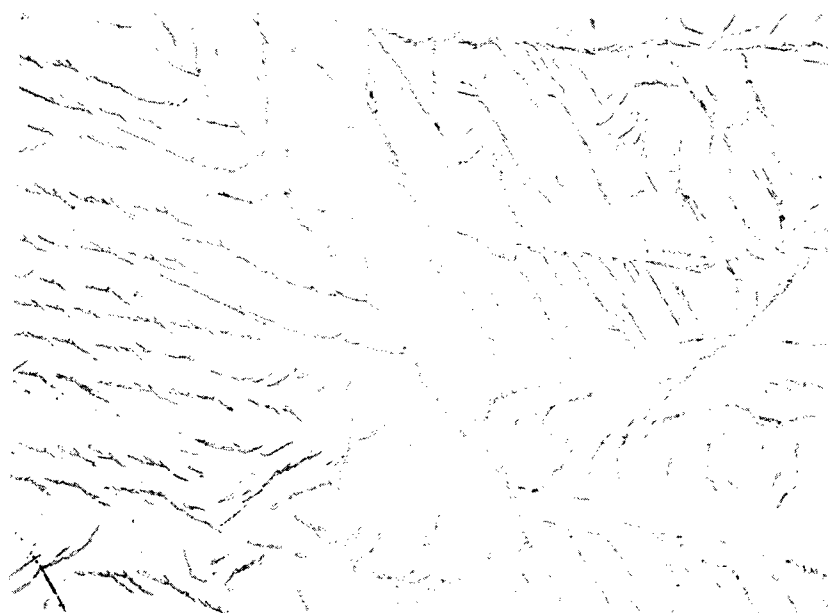
Figure 12. COMPARISON OF BEND DUCTILITIES OF ARC-WELDED AND UNWELDED TITANIUM-CARBON ALLOY SHEETS

Weld
Zone

Heat
Affected
Zone

Weld and Heat-Affected Zone

Weld

FIGURE 13. STRUCTURES WHICH OCCUR IN WELD ZONE OF
TITANIUM – 0.74 PER CENT CARBON-ALLOY SHEET

FIGURE 14. END OF CRACK IN PARTIALLY FRACTURED
ARC-WELDED BEND SPECIMEN IN TITANIUM-
0.55 PER CENT CARBON-ALLOY SHEET

the weld is shown in the upper photomicrograph. The other photomicrograph shows the carbide network structure in the weld itself at higher magnification.

Examination of a number of bend specimens cut from welded sheets of the 0.55 and 0.74 per cent carbon alloys has shown that fractures and cracks in these bend specimens tend to follow the carbide network. This is shown in Figure 14. This figure shows the end of a major crack which occurred in a weld during bend testing. It can be seen that the crack has followed the carbide, sometimes splitting the carbide inclusion into two parts. It can also be seen that some of the other carbides have cracked.

When the carbon content is high enough to be above the solid-solubility limit of carbon in the alpha titanium, heat treatment will not affect the ductility of the weldment except possibly by spheroidizing the carbides. However, with lower carbon content alloys, the 0.28 per cent alloy, for example, heat treatment may affect the amount of carbide present in the weld. In this alloy, welds contain the stringer-type carbide which is found in welds in the higher carbon alloys. Of course, there is much less of it than is found in welds in the 0.55 and 0.74 per cent alloys. These carbides precipitate out during freezing and the cooling rate is fast enough to prevent their being taken into solution in the alpha titanium. As can be seen from the phase diagram in Figure 15, the carbide has low solubility in beta titanium. Consequently, a quench from temperatures in the beta field produces alpha which is not saturated with carbon even when the carbon content is near the limit of solid solubility. Heat treatments at temperatures high in the alpha field saturate the alpha with carbon and increase its hardness and strength. The hardness of the weld metal in 0.28 per cent carbon sheet is raised by 30 to 50 Vickers by being heated at 1500 F for four hours after welding. On the fully annealed base metal, such a treatment has no effect on hardness. This treatment does not affect the ductility of the weldment appreciably. Even in the as-welded condition the 0.28 per cent alloy weld contains only a few carbide stringers, and removal of these by heat treatment has little effect on ductility of the weldment. It does however shift the place where fracture occurs in a bend specimen from the base metal to the weld. In the as-welded bend specimen the base metal is harder (20 to 25 Vickers) than the weld and is less ductile. After heat treatment the weld is harder than the base metal and consequently is less ductile.

The properties of spot welds in the titanium-carbon-alloy sheets are given in Table 7. So far as tension-shear strengths are concerned, carbon in amounts as high as 0.55 per cent had little effect. However, the cross-tension strength starts to decrease at a carbon content of 0.28 per cent.
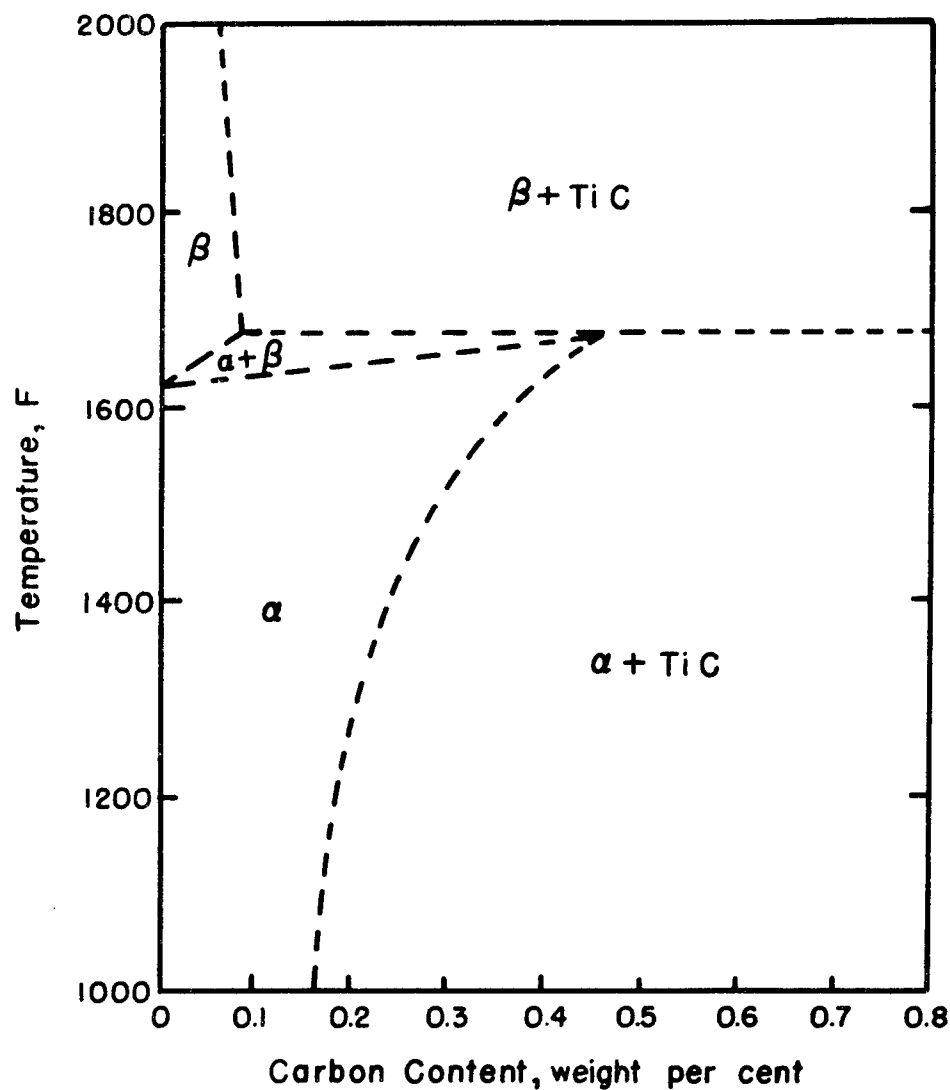
Note: From paper on "Alloys of Titanium with Carbon, Oxygen,
and Nitrogen," by R.I. Jaffee, H.R. Ogden, and D.J. Maykuth,
Journal of Metals, Transactions AIME, Vol. 188, October,
1950

Figure 15. PART OF TENTATIVE EQUILIBRIUM DIAGRAM
FOR TITANIUM-CARBON ALLOYS

TABLE 7. STRENGTH PROPERTIES OF SPOT WELDS IN SPONGE TITANIUM-CARBON ALLOYS

Composition	Sheet Thickness, in.	Nugget Diameter	Tension-Shear Strength, lb	Cross-Tension Strength, lb	Tension-Shear Ratio	Maximum Hardness, Vickers
Unalloyed Sponge. 0.03% Carbon	0.032	5T	1100	500	0.45	240
	0.064	3T	2400	900	0.37	222
0.13% Carbon	0.032	5T	1250	525	0.42	268
	0.064	3T	2500	1500	0.60	249
0.28% Carbon	0.032	5T	1000	300	0.30	330
	0.064	3T	2600	800	0.31	306
0.55% Carbon	0.032	5T	1100	200	0.18	314
	0.064	3T	2400	300	0.13	294
0.74% Carbon	0.032	5T	1000	40	0.04	345
	0.064	3T	1600	300	0.19	314

In sheets containing 0.55 per cent carbon or more, the cross-tension strength becomes very low, and, consequently, the tension-shear ratio becomes very low.

The reason for the drop in the cross-tension strength with increasing carbon content appears to be the network carbides which are present in the weld. This is the same type of structure as was found in arc welds in the higher carbon alloys except that in the spot welds it is much finer. Figure 16 shows the appearance of the carbide in a spot weld in 0.55 per cent carbon sheet. The carbide embrittles the weld and the cross-tension specimens fracture with much less deformation than is obtained with the spot welds which do not contain carbides. Generally, the spot-weld specimens in the high-carbon alloys shatter when they break during testing.

Properties of Welded Titanium-Oxygen Alloys

The strength properties of arc-welded titanium-oxygen alloys are given in Table 8. The addition of 0.15 per cent oxygen to titanium has no bad effects on the properties of arc welds. The tensile strength of weldments is raised and the tensile elongation is somewhat lower than for the unwelded sheet. This is due to the higher strength of the weld, which forces nearly all of the deformation to occur in the heat-affected zone and unaffected base metal. The bend ductility of the welded 0.15 per cent oxygen sheet is about the same as for unwelded sheet and is not too much lower than that of weldments in unalloyed sponge sheet.

For oxygen contents of 0.30 per cent, the story is quite different. Welds in the alloy have much lower bend ductilities than unwelded sheet of the same composition. This is not caused by any difference in structure that occurs in the weld, as was the case with the carbon alloys. The welds in the 0.30 per cent oxygen-alloy sheet contain numerous small cracks as welded and these appear to be the cause of the low bend ductility. Figure 17 shows a crack in a weld made in 1/8-inch titanium-0.30 per cent oxygen sheet. The same type of crack can also occur in the heat-affected zone and in the unaffected base metal, as is shown in Figure 18. These cracks are not present in the base metal before welding. They do not appear to be associated with any structural factors although they might be caused by segregation of oxygen, particularly in the weld metal. The cracks may also be caused by some type of hot shortness in the higher oxygen alloys.

Welds in the 0.55 per cent oxygen alloy have very low tensile and bend ductility. Here again the cause seems to be cracks in the weld and
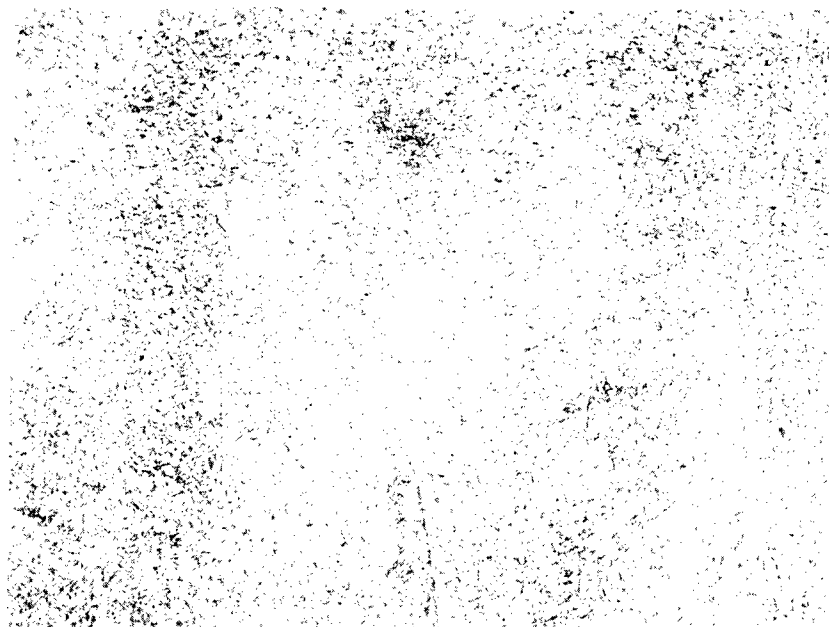
FIGURE 16. AREA IN SPOT-WELD NUGGET IN TITANIUM – 0.55
PER CENT CARBON ALLOY. ACICULAR STRUCTURE
IS CARBIDE NETWORK

TABLE 8. STRENGTH PROPERTIES OF ARC WELDS IN SPONGE TITANIUM-OXYGEN-ALLOY SHEET

| Nominal Composition (Addition made during melting)	Sheet Thickness, in.	Tensile Strength, psi	Elongation in 2 in., per cent	Reduction of Area, per cent	Minimum Bend Radii Longitudinal	Minimum Bend Radii Transverse	Maximum Hardness, Vickers
Unalloyed Sponge (Process A)	0.064	70,800	22	37	3T	1-1/2T	209
	0.125	69,500	21	41	1-1/2T	2T	210
0.15% Oxygen	0.064	96,000	10	24	3T	2T	283
	0.125	96,900	15	24	4T	3T	279
0.30% Oxygen	0.064	101,000	12	15	12T	> 12T	339
	0.125	109,000	10	14	> 12T	> 12T	345
0.55% Oxygen	0.064	103,000	0	2	> 12T	> 12T	363
	0.125	125,000	1.5	1	> 12T	> 12T	339
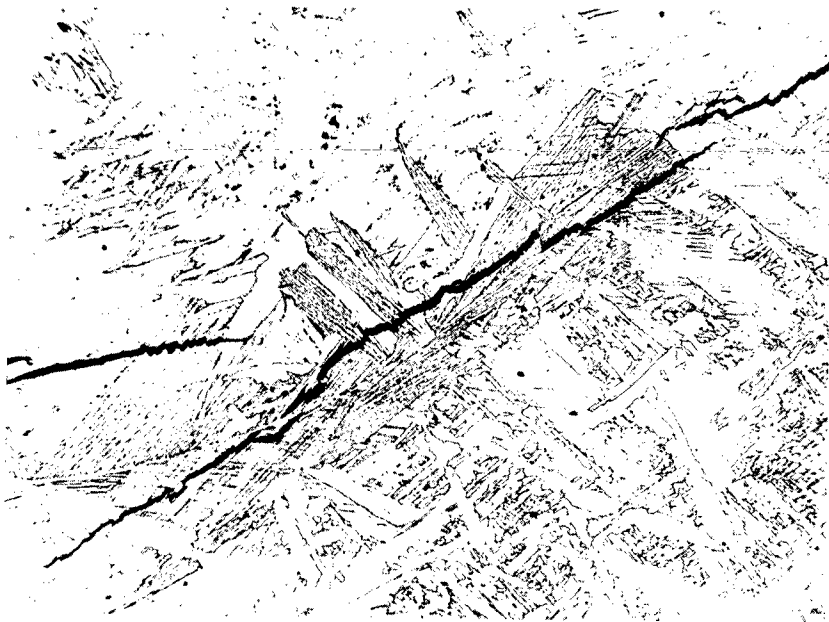
FIGURE 17. CRACK IN WELD METAL IN TUNGSTEN ARC WELD IN TITANIUM - 0.30 PER CENT OXYGEN ALLOY SHEET

FIGURE 18. CRACK IN UN-AFFECTED BASE METAL JUST OUTSIDE HEAT-AFFECTED ZONE OF WELD IN TITANIUM - 0.30 PER CENT OXYGEN-ALLOY SHEET

base metal near the weld zone. Welds in this alloy contain many more cracks than welds in the 0.30 per cent oxygen alloy.

The results of spot-weld tests in the titanium-oxygen-alloy sheet are given in Table 9. Oxygen does not have an adverse effect on tension-shear load until the amount present is somewhat greater than 0.30 per cent. The effect on cross-tension strength was noticeable in the 0.032-inch sheet at 0.15 per cent oxygen. In the 0.064-inch sheet, however, it was not particularly noticeable except in the 0.55 per cent oxygen sheet. The welds in both thicknesses of sheet had about the same hardnesses and no cracked welds were found in the samples which were metallographically examined. Apparently the difference in behavior between the spot welds in the two sheet thicknesses was caused by the different geometry of the spots. As can be seen from the table, the spot weld is larger in terms of sheet thickness in the thinner sheet. It was necessary to use the proportionally larger spot in the thinner sheet to obtain consistent strength values.

Properties of Welds in Titanium-Nitrogen -Alloy

The strength properties of arc welds in titanium-nitrogen-alloy sheets are given in Table 10. It is apparent that nitrogen affects the properties of welds in titanium at much lower levels than either carbon or oxygen. Welds in sheet containing 0.13 per cent nitrogen have poor bend ductility. As in the oxygen alloys, cracks in the weld such as shown in Figure 19 appear to be the cause of the poor bend ductility. In the 0.24 per cent nitrogen alloy, the weld, heat-affected zone, and the unaffected base metal adjacent to the heat-affected zone contain cracks. This is shown in Figure 20. There was no indication that the sheets of either of these alloys contained cracks prior to welding.

The properties of spot welds in the titanium-nitrogen-alloy sheets are given in Table 11. As in the arc-welded specimens, the properties of spot welds in sheet containing 0.13 per cent nitrogen are rather poor. This is particularly shown by the tension-shear ratio. The low cross-tension strengths obtained with the nitrogen alloys does not appear to be caused by cracks in the spot welds. It apparently is a result of the low ductility which is a property of the alloys.

TABLE 9. PROPERTIES OF SPOT WELDS IN SPONGE TITANIUM-OXYGEN SHEET

Composition	Sheet Thickness, in.	Spot Diameter, in.	Tension-Shear Strength, lb	Cross-Tension Strength, lb	Tension-Shear Ratio	Maximum Hardness, Vickers
Unalloyed Sponge (Process A)	0.032	5T	1100	500	0.45	240
	0.064	3T	2400	900	0.37	222
0.15% Oxygen	0.032	5T	1150	300	0.26	268
	0.064	3T	2600	1200	0.46	285
0.30% Oxygen	0.032	5T	1100	140	0.13	333
	0.064	3T	2800	900	0.32	336
0.55% Oxygen	0.032	5T	525	0	0	390
	0.064	3T	1250	60	0.05	363

TABLE 10. STRENGTH PROPERTIES OF ARC WELDS IN SPONGE TITANIUM-NITROGEN-ALLOY SHEET

Composition	Sheet Thickness, in.	Tensile Strength, psi	Elongation in 2 in., per cent	Reduction of Area, per cent	Minimum Bend Radii Longitudinal	Minimum Bend Radii Transverse	Maximum Hardness, Vickers
Unalloyed Sponge (Process A)	0.064	70,800	22	37	3T	1-1/2T	209
	0.125	69,500	21	41	1-1/2T	2T	210
0.13% Nitrogen	0.064	113,000	13	16	8T	>12T	306
	0.125	105,000	8	9	12T	12T	322
0.24% Nitrogen	0.064	120,000	0	0	>12T	>12T	317
	0.125	120,000	0	0	>12T	>12T	360

TABLE 11. STRENGTH PROPERTIES OF SPOT WELDS IN SPONGE TITANIUM-NITROGEN-ALLOY SHEET

Composition	Sheet Thickness, in.	Spot Diameter, in.	Tension-Shear Strength, lb	Cross-Tension Strength, lb	Tension-Shear Ratio	Maximum Hardness, Vickers
Unalloyed Sponge (Process A)	0.032	5T	1100	500	0.45	240
	0.064	3T	2400	900	0.37	222
0.13% Nitrogen	0.032	5T	800	220	0.28	351
	0.064	3T	2750	400	0.15	330
0.24% Nitrogen	0.032	5T	1000	33	0.03	333
	0.064	3T	2100	300	0.14	346
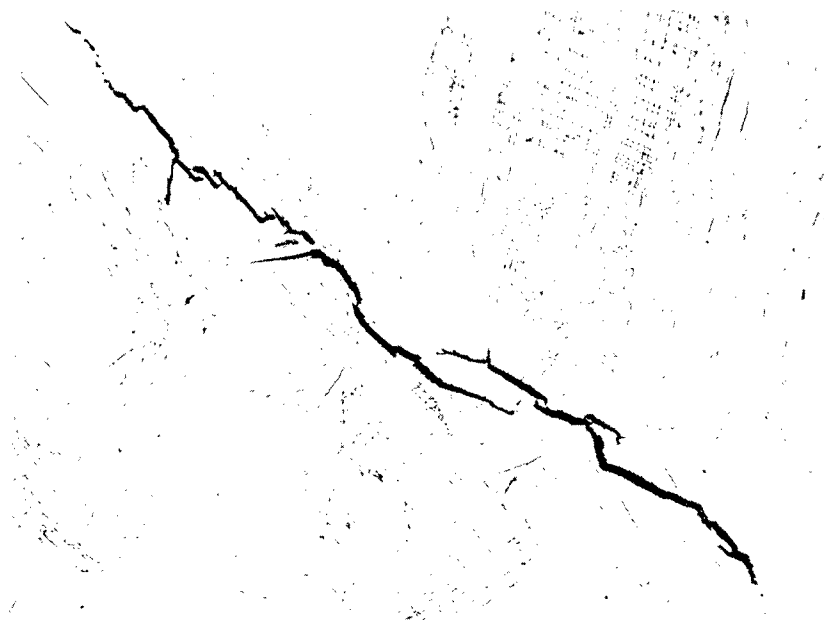
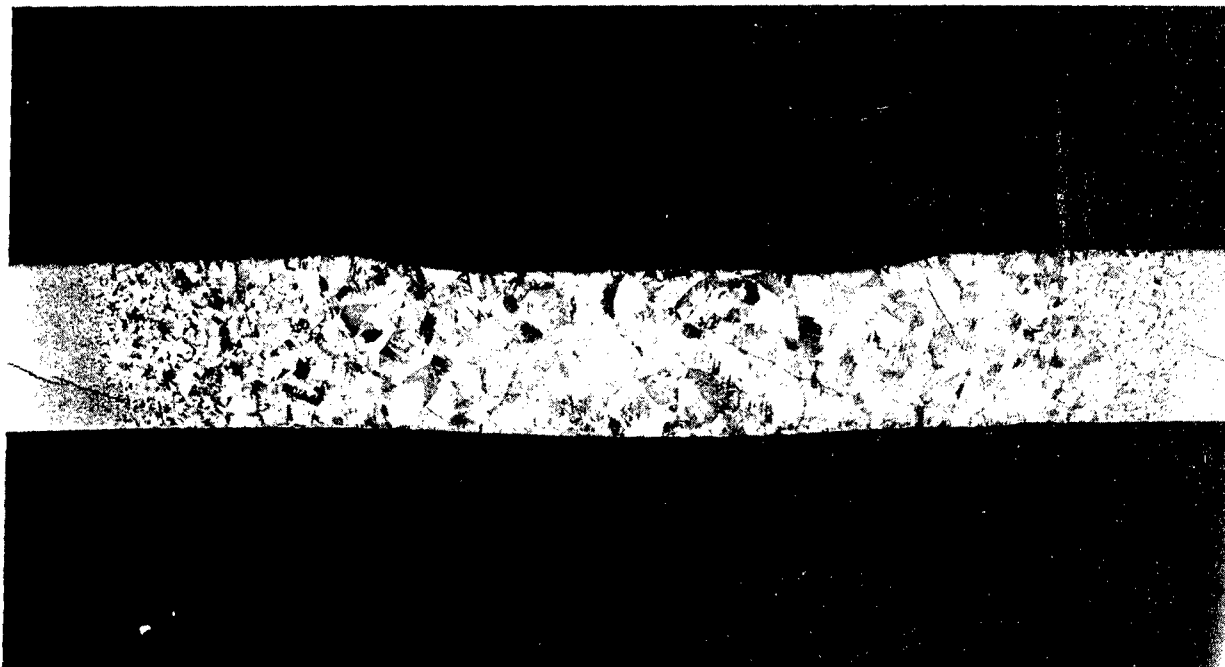FIGURE 19. CRACKS IN WELD-METAL ARC WELD IN TITANIUM –
0.13 PER CENT NITROGEN ALLOY

FIGURE 20. PHOTOMACROGRAPH OF ARC WELD IN 1/8-INCH, TITANIUM -
0.24 PER CENT NITROGEN-ALLOY SHEET

FIGURE 21. EXAMPLE OF POROSITY OBTAINED IN ARC WELD IN 1/8-INCH
TITANIUM SHEET

Examination of radiographs of arc welds made during this investigation has shown that porosity can be a problem in titanium welds. Figure 21 shows a typical example of a porous weld in one of the titanium-alloy sheets. There seemed to be no correlation between alloy content and porosity. There was some correlation between sheet thickness and porosity, most porosity occurring in 1/8-inch sheet. It was possible to decrease porosity by using higher welding currents or slower welding speeds.

The suspected cause of porosity in titanium welds is hydrogen. Other gases which might be encountered react so readily with titanium that it is difficult to see how they could cause porosity. Hydrogen is known to have a fairly low solubility in beta titanium. If the solubility of hydrogen is high in liquid titanium, rejection during freezing as a gas could cause porosity.

CONCLUSION

Carbon, oxygen, and nitrogen can cause brittleness in welds in titanium when present in sufficient amounts. To avoid brittle welds, carbon and oxygen should be kept below the following amounts:

Carbon - 0.28 per cent

Oxygen - 0.15 per cent

The data show that 0.13 per cent nitrogen is enough to produce poor properties in welds in titanium sheet. Unfortunately, it is not possible to say just what the maximum nitrogen content should be. Information is needed on the properties of welds in sheet containing 0.05 to 0.10 per cent nitrogen to determine the maximum tolerable amount. An estimate of the maximum nitrogen content based on the available data is 0.05 per cent, but additional work is needed to determine whether this estimate is correct.

The adverse effects of these elements occur at relatively low concentrations. This points out the necessity for maintaining good shielding during welding. It is known that as much as 0.20 per cent nitrogen can be picked up when multipass tungsten-arc welds are made with shielding which appears to be normal but is apparently inadequate. Consequently, the use of trailing shields and gas backups is recommended when titanium is to be welded.

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